

S. Okada · D.A. Bennett · W.B. Doriese ·  
 J.W. Fowler · K.D. Irwin · S. Ishimoto ·  
 M. Sato · D.R. Schmidt · D.S. Swetz ·  
 H. Tatsuno · J.N. Ullom · S. Yamada

# High-resolution kaonic-atom x-ray spectroscopy with transition-edge-sensor microcalorimeters

26.07.2013

**Abstract** We are preparing for an ultra-high resolution x-ray spectroscopy of kaonic atoms using an x-ray spectrometer based on an array of superconducting transition-edge-sensor microcalorimeters developed by NIST. The instrument has excellent energy resolutions of 2 – 3 eV (FWHM) at 6 keV and a large collecting area of about 20 mm<sup>2</sup>. This will open new door to investigate kaon-nucleus strong interaction and provide new accurate charged-kaon mass value.

**Keywords** Kaonic atom, X-ray spectroscopy, Transition-edge sensor

## 1 Introduction

Any negatively charged leptons or hadrons (e.g.,  $\mu^-$ ,  $\pi^-$ ,  $K^-$ ,  $\bar{p}$ ,  $\Sigma^-$ ) apart from the conventional electrons can be bound by the Coulomb field of an atomic nucleus. The Coulomb-bound system, so-called exotic atom, is essentially a hydrogen-like atom except for its short lifetime and the large reduced mass resulting in unusually small orbital radii. In the case of a hadron feeling strong interaction with the atomic nucleus, so-called hadronic atom, because of being short-range force, the effects appear in the most tightly bound energy level being the most perturbed

---

S. Okada · M. Sato · S. Yamada  
 RIKEN Nishina Center, RIKEN, Wako, 351-0198, Japan  
 E-mail: sokada@riken.jp

D.A. Bennett · W.B. Doriese · J.W. Fowler · K.D. Irwin · D.R. Schmidt · D.S. Swetz ·  
 J.N. Ullom  
 National Institute of Standards and Technology, Boulder, CO 80303, USA

S. Ishimoto  
 High Energy Accelerator Research Organization, Ibaraki 305-0801, Japan

H. Tatsuno  
 Laboratori Nazionali di Frascati, INFN, I-00044 Frascati, Italy

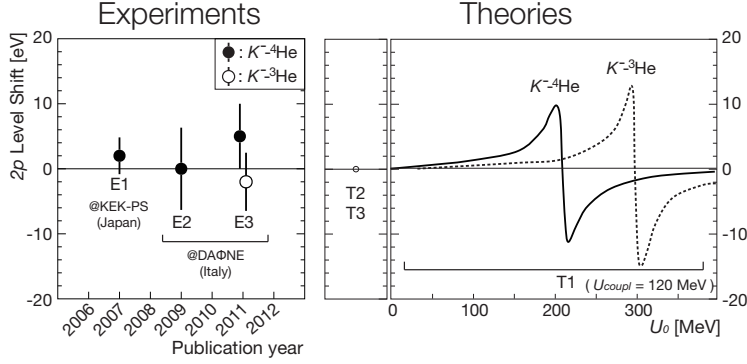
by the strong force as a shift from that given only by the electromagnetic interaction, and a broadening due to absorption of the hadron by the nucleus. The shift and width can be experimentally extracted from characteristic x-ray-emission spectroscopy of the hadronic-atom x-rays feeding the low-lying state. This offers a unique opportunity to investigate the strong interaction between hadron and nucleus (or nucleon) at the low energy limit which is unobtainable in typical scattering experiments.

Anti-kaon  $\bar{K}$ , namely  $K^-$  or  $\bar{K}^0$ , is the lightest hadron containing a strange valence quark. The low-energy  $\bar{K}N$  system has attracted attention as a testing ground for chiral SU(3) dynamics in low-energy QCD and the role of the interplay between spontaneous and explicit chiral symmetry breaking due to the relatively large mass of the strange quark.

In the simplest kaonic atom, i.e., kaonic hydrogen ( $K^-p$ ), the  $1s$ -atomic-state shift and width deduced from the spectroscopy of  $2p-1s$  transition of the  $K^-p$  atom x-rays at  $\sim 6.5$  keV are directly related to the real and imaginary parts of the complex  $K^-p$   $S$ -wave scattering length. Therefore the data have been intensively collected so far<sup>1,2,3</sup>. The results indicate that  $\bar{K}N$  interaction in low energy is strongly attractive, which leads to particular interests in the depth of the real  $K^-$ -nucleus potential at zero energy in connection with possible kaon condensation in astrophysical scenarios (e.g., neutron star) and the possible existence of “deeply-bound nuclear  $K^-$  states”.

Many experiments have collected data on a variety of targets other than kaonic hydrogen atom so far<sup>4</sup>. Despite of the fact most of theories reproduce the data<sup>4,5</sup>, there has been a conflict in the potential depth between phenomenological potentials and potentials constructed from more fundamental approaches. The former are typically 180 MeV deep, whereas the latter are less than 50 MeV deep. Apart from kaonic-atom experiments, a lot of experimental search for the deeply-bound nuclear  $K^-$  states have been performed in a past decade; however, only a small amount of information is available<sup>6,7</sup>, which is not sufficient to discriminate between a variety of conflicting interpretations.

Recently, the kaonic-helium atom ( $K^-$ -He) has attracted interest in connection with the theoretical predictions<sup>8,9</sup> that a large shift and width of the  $2p$  level may appear near the resonance between atomic and nuclear poles, which is closely related to the existence of deeply bound nuclear  $K^-$  states. A recent calculation<sup>9</sup> shows the shift and width as a function of the real part ( $U_0$ ) of the potential depth at a certain coupled potential depth ( $U_{coupl}=120$  MeV) with the different values for  $K^-$ - $^3\text{He}$  and  $K^-$ - $^4\text{He}$  atoms as shown in Fig.1. The calculation was based on the coupled-channel approach between the  $\bar{K}N$  channel and the  $\Sigma\pi$  decay channel. A large shift of  $|\epsilon_{2p}| \sim 10$  eV and width of  $|\Gamma_{2p}| \sim 20$  eV are predicted for  $K^-$ - $^4\text{He}$  when the potential depth is at around  $\sim 200$  MeV, whereas most of theoretical calculations predict smaller values, e.g.,  $\epsilon_{2p} \sim -0.2$  eV and  $\Gamma_{2p} \sim 2$  eV<sup>8</sup>. Measurements of  $3d-2p$  transitions in  $K^-$ - $^3\text{He}$  (6.2 keV) and  $K^-$ - $^4\text{He}$  (6.5 keV) have been performed so far with the conventional semiconductor spectrometers having the FWHM energy resolution of typically  $\sim 200$  eV at 6 keV<sup>11,12,13</sup>, which is insufficient to see such a small spectral effects due to the strong interaction.



**Fig. 1** The  $2p$ -level shift of  $K^{-3}\text{He}$  and  $K^{-4}\text{He}$  atoms obtained from the recent experiments (left) at KEK-PS (E1<sup>11</sup>) and DAΦNE (E2<sup>12</sup>, E3<sup>13</sup>) compared with the theoretical calculations (right). A recent calculation by the use of the coupled-channel model as a function of the real part ( $U_0$ ) of the potential depth at a coupled potential depth of  $U_{\text{coupl}}=120$  MeV (T1<sup>9</sup>), compared with other calculations showing shifts being very close to zero (T2<sup>4</sup>, T3<sup>5</sup>). Experimental results so far are not accurate enough to distinguish between different models.

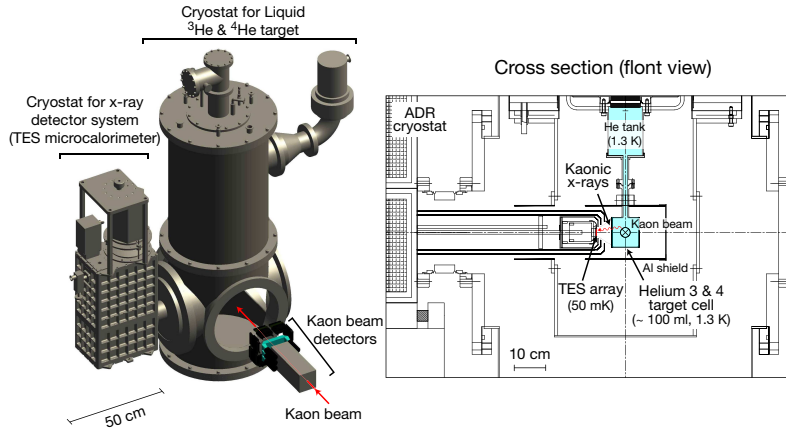
## 2 A proposed experiment

Aiming at a breakthrough to the current situation, we are planning to perform ultra-high-resolution x-ray spectroscopy of kaonic atoms using an array of NIST's transition-edge-sensor (TES) microcalorimeters having a FWHM energy resolution of 2 – 3 eV at 6 keV, being two order of magnitude improved resolution compared with the conventional semiconductor detector. The TES is a thermal sensor that measures an energy deposition by the increase of resistance of a superconducting film biased within the superconducting-to-normal transition. The detailed working principles and the recent progress of the NIST's TES system are described in Refs. <sup>14,15</sup>. A preliminary result of a recent test measurement shows an excellent FWHM time resolution of  $\sim 0.5$   $\mu\text{sec}$  as well. Now we are preparing another test measurement at a hadron beamline to evaluate an in-beam performance of the x-ray spectrometer.

We plan to use a NIST-designed 160 pixel TES array each having 350  $\mu\text{m}$  square collecting area per pixel, being  $\sim 20$   $\text{mm}^2$  in total, together with a time-division SQUID multiplexer readout system. For the cryostat, we utilize a pulse-tube adiabatic demagnetization refrigerator (ADR) developed by NIST and HPD, 102 DENALI<sup>16</sup>, whose base temperature is 50 mK. The size of this system is 33 cm  $\times$  22 cm  $\times$  66 cm tall which is relatively portable and compact. The portability is essential for our experiment constrained by very limited and busy beam time.

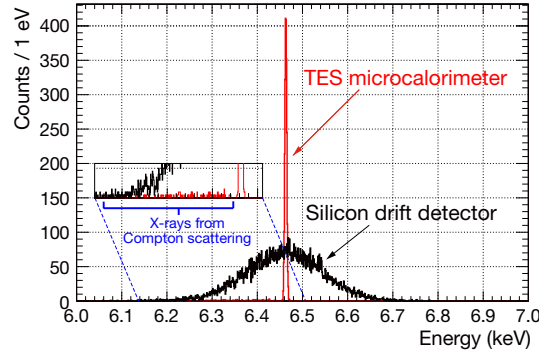
The experiment will be performed at a kaon beamline at J-PARC hadron hall, e.g., K1.8BR beamline<sup>17</sup>. Kaons are produced by bombarding the production target (Ni, Ag or Pt) with the primary proton beam from J-PARC 50 GeV proton synchrotron, and extracted through the kaon beamline. The kaonic-helium atoms are created by stopping kaons in a helium target.

Fig.2 shows a possible experimental setup. Incident kaons extracted with a momentum of  $\sim 900$  MeV/c are degraded in carbon degraders, counted with beamline counters together with Lucite Čerenkov counters for reducing the



**Fig. 2** (Color online) A schematic birds-eye view (left) and a cross section front view (right) of a possible experimental setup around the experimental target. A set of beam detectors, a cryogenic liquid- $^3\text{He}$  and  $^4\text{He}$  target system, and a NIST's TES x-ray spectrometer system are shown.

**Fig. 3** (Color online) Simulated spectra of the  $3d-2p$  transitions of kaonic- $^4\text{He}$  atoms detected by different x-ray detectors: a conventional silicon drift detector with a FWHM energy resolution of 190 eV at the energy, and a TES microcalorimeter with a FWHM energy resolution of 5 eV.



pion contamination, tracked by a high-rate beamline drift chamber and stopped inside the liquid-helium target. To ensure that kaons are stopped in the target, an anti-coincidence counter is installed just downstream side of the target. X-rays emitted from the  $K^-$ -He atoms are detected by a TES spectrometer viewing the target from a side.

The main trigger will be defined by the beamline counters to identify incoming kaons and the anti-coincidence counter to ensure stopped kaons in the target. X-ray signals of TES are coincident with the trigger to reduce accidental backgrounds.

Fig.3 is a result of a GEANT4 simulation where  $K^-$ - $^4\text{He}$   $3d-2p$  x-rays are measured by different two x-ray detectors. One is a typical conventional silicon drift detector used in the previous experiments<sup>11,12,13</sup> having a  $400\text{-}\mu\text{m}$ -thick active layer with  $100\text{ mm}^2$  collecting area and 190 eV (FWHM) energy resolution. The other is a TES spectrometer having  $5\text{-}\mu\text{m}$ -thick Bi absorbers with  $20\text{ mm}^2$  collecting area and 5 eV (FWHM) energy resolution.

In the previous experiment<sup>11</sup>, there has been a non-negligible effect of spectral distortion due to Compton scattering in the liquid  $^4\text{He}$  target. As shown in

Fig.3, the effect is completely separated from the distinct x-ray peak measured by TES. Although the other experiments<sup>12,13</sup> utilised a gaseous helium target so as to reduce the effect, we can now use a liquid helium target to efficiently stop kaons without suffering the Compton scattering problem.

A lot of fluorescence x-rays (e.g., Fe  $K_{\alpha 1}$  6.40 keV, Fe  $K_{\alpha 2}$  6.39 keV and Mn  $K_{\beta}$  6.49 keV) and kaonic x-rays other than  $K^-$ -He x-rays were possible serious background sources in the past experiments. In reversal, these are rather useful as good calibration lines in the proposed measurement with a TES spectrometer. The precise energy calibration is essential in such a high resolution measurement; and thus we will carefully select our calibration sources of the fluorescence x-rays whose energies, width and satellite peaks are well known. Moreover a simultaneous measurement of  $3d-2p$  x-rays in  $K^-$ - $^4\text{He}$  (6.5 keV) and  $K^-$ - $^3\text{He}$  (6.2 keV) atoms with a mixed liquid  $^3\text{He}$  and  $^4\text{He}$  target is possible, which will drastically reduces the systematic errors of relative x-ray energies and widths for both atoms.

Referring the yield of  $K^-$ - $^4\text{He}$   $3d-2p$  x-rays obtained in the previous experiment<sup>11</sup>, the yield was roughly estimated to be about 30 events per day assuming that the J-PARC K1.8BR beamline is employed with an operational proton beam power of 60 kW. Four-days data acquisition will give about 120 events resulting in a statistical error of 0.1 eV in x-ray energy, assuming 2 – 3 eV (FWHM) energy resolution without background. Thus, we could obtain more than one order of magnitude improved statistical errors of the x-ray energy and the width values compared to the previous experiments with a reasonable data acquisition time.

As well as  $K^-$ -He atoms, there is another theoretical suggestion of a precise measurement of  $3d-2p$  x-rays in  $K^-$ - $^6\text{Li}$  and  $K^-$ - $^7\text{Li}$  ( $\sim 15$  keV), whose result has a possibility to discriminate between deep (phenomenological) or shallow (chiral) potentials<sup>18</sup>. Moreover there are other remarkable studies using ultra-high-resolution kaonic x-ray spectroscopies with TES spectrometers we intend to perform as follows:

1. Charged kaon mass measurement: Kaonic-atom x-ray spectroscopy has been also utilized as a tool for measuring the charged kaon mass. The latest value is determined by the average of the six measurements to be  $493.677 \pm 0.013$  MeV ( $S=2.4$ )<sup>19</sup>. This relatively large error mainly comes from two data whose central values differ vastly about 60 keV; thus a new accurate measurement has been eagerly awaited. We aim to improve the precision of this mass measurement with a high-precision measurement of  $K^-$ - $^{12}\text{C}$   $5-4$  x-ray ( $\sim 10$  keV). The precision is expected to be  $\sim 2.5$  keV corresponding to the accuracy of  $\sim 0.05$  eV for the x-ray energy.
2. Study of  $K^-$  multi-nucleon absorption process: Recent theoretical studies of strong interaction effects in kaonic atoms suggest that analysing so-called 'lower' and 'upper' levels in the same atom could separate one-nucleon absorption from multinucleon processes<sup>20</sup>. For this study, direct measurements of upper level widths in addition to lower level widths are essential for medium-weight and heavy kaonic atoms (100 – 450 keV x-rays) whose candidates were examined recently<sup>21</sup>. The measurements will be performed in future with a gamma-ray TES spectrometer similar to what NIST has already achieved, having a 256 pixel array resulting in  $5\text{ cm}^2$  collecting area and an averaged FWHM energy resolution of 53 eV at 100 keV<sup>15</sup>.

### 3 Conclusions

We are preparing a next-generation kaonic-atom x-ray spectroscopy using an x-ray spectrometer based on an array of superconducting TES microcalorimeters developed by NIST. Precise measurements of  $3d-2p$  x-rays in kaonic-helium atoms ( $\sim 6$  keV) and kaonic-lithium atoms ( $\sim 15$  keV) with two order of magnitude improved energy resolution compared with the conventional silicon detectors will enable us to see small spectral effects due to the strong interaction. This will add a fresh dimension to the study of the depth of the real  $K^-$ -nucleus potential at zero energy in connection with the existence of deeply-bound nuclear  $K^-$  states. Additionally, we intend to improve the precision of the charged kaon mass measurement with high-precision measurement of  $K^-$ - $^{12}\text{C}$   $5-4$  x-ray ( $\sim 10$  keV), and study the  $K^-$  multi-nucleon absorption process in future with direct measurements of upper level widths in medium-weight and heavy kaonic atoms using a multi-pixel TES spectrometer with a useable dynamic range above 400 keV.

**Acknowledgements** This work was supported by JSPS KAKENHI Grant Number 25105514 and by Incentive Research Grant from RIKEN.

### References

1. M. Iwasaki, *et al.*, Phys. Rev. Lett. **78** (1997) 3067;  
T. M. Ito, *et al.*, Phys. Rev. C **58** (1998) 2366.
2. G. Beer, *et al.* (DEAR Collaboration), Phys. Rev. Lett. **94** (2005) 212302.
3. M. Bazzi, *et al.* (SIDDHARTA Collaboration), Phys. Lett. B **704** (2011) 113;  
M. Bazzi, *et al.* (SIDDHARTA Collaboration), Nucl. Phys. A **881** (2012) 88.
4. C. J. Batty, E. Friedman and A. Gal, Phys. Reports **287**, 385 (1997).
5. S. Hirenzaki, Y. Okumura, H. Toki, E. Oset, and A. Ramos, Phys. Rev. C **61**, 055205 (2000).
6. M. Agnello *et al.*, Phys. Rev. Lett. **94**, 212303 (2005).
7. T. Yamazaki *et al.*, Phys. Rev. Lett. **104**, 132502 (2010).
8. C. J. Batty, Nucl. Phys A **508** (1990) 89c.
9. Y. Akaishi, proceedings for *International Conference on Exotic Atoms (EXA05)*, Austrian Academy of Sciences Press, Vienna, 2005, p. 45.
10. E. Friedman, private communication.
11. S. Okada, *et al.*, Phys. Lett. B **653** (2007) 387.
12. M. Bazzi, *et al.* (SIDDHARTA Collaboration), Phys. Lett. B **681** (2009) 310.
13. M. Bazzi, *et al.* (SIDDHARTA Collaboration), Phys. Lett. B **697** (2011) 199.
14. C. Enss (ed.), Cryogenic Particle Detection, Topics in Applied Physics, vol. **99**, Springer, 2005.
15. D.A. Bennett *et al.*, Rev. Sci. Instrum. **83** (2012) 093113.
16. <http://www.hpd-online.com>
17. K. Agari *et al.*, Prog. Theor. Exp. Phys. (2012) 02B011.
18. S. Hirenzaki, Private communication.
19. J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86** (2012) 010001.
20. E. Friedman, A. Gal, Nucl. Phys. A **899** (2013) 60.
21. E. Friedman and S. Okada, Nucl. Phys. A **915** (2013) 170.